Memory Management Replay in DejaVu

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Abstract— **Multithreading makes it hard to use cyclic debugging techniques, due to the non-determinism related to the concurrent behaviour of such applications. A well known solution consists of recording an execution and debugging it during replay. In order to produce a faithful replay, the recorded information needs to contain enough information to cover all non-deterministic choices. Java has an extra source of non-determinism related to the garbage collector of the JVM. This paper discusses the problems that arise herefrom and describes the solutions we developed in order to implement a fully operational memory management replay module, based on the scheduling replay of DejaVu.**

Keywords— **Record/replay, DejaVu, multithreading, debugging, Java**

I. Introduction

DejaVu is a record/replay framework, developed at IBM [CS98], [CAN+01]. In its most recent version it replays an application by recording the points where thread switches were made and forcing them to happen again at the very same points during replay. Furthermore, wall-clock values are also recorded and replayed, because these values can also influence thread scheduling. Other forms of non-determinism, like file-input, are not handled because of efficiency, although functionality to do so is present. Remark however that replaying the thread switch points only works on a single processor.

DejaVu has been developed for, among others, Jikes RVM [Jik02]. This virtual machine is almost entirely written in Java and can therefore benefit from cross-optimization to improve its performance. Cross-optimization means that the runtime environment and the application are analysed together, clearing the road for more intrusive optimization techniques. Co-running a record/replay functionality with such a virtual machine can also benefit from the same performance improvement. This is exactly what DejaVu does. Unfortunately, this also means that DejaVu, as part of the bigger picture, also has to behave similarly during record and replay. However, this imposes that DejaVu should replay itself, which is by definition impossible. The rest of the paper presents how to deal with this contradictio in terminis.

II. Problem statement

Cyclic debugging of multithreaded applications is difficult, due to the non-deterministic nature of their concurrent behaviour. A lot of record-replay mechanisms have been introduced to cope with this kind of difficulty [CGC+03]. Known sources of non-determinism are: actions by the scheduler, interrupts, input (e.g. the clock values), and data races. In Java however, there is an additional source of non-determinism, namely the invocation points of the garbage collector in a particular execution. This non-determinism could further influence the application, for instance in the presence of address-based hashing techniques.

There are two ways to deal with the non-determinism of the GC: one could record the execution points at which the garbage collector is invoked, and re-invoke it during replay at the very same points, or one could enforce the application to behave deterministically in accordance to the memory manager, such that the garbage collector will automatically be invoked at the same execution points. Both have their own problems: re-invoking the garbage collector requires that the replay phase does not use more memory than the original one. Furthermore, this method can never guarantee the same memory layout and object references. Deterministically replaying all the memory allocation operations effectively solves this problem, but it is not straightforward either: it must be done for both the application and the instrumentation code. Especially the latter one is difficult since the instrumentation code for record-

ing and replaying is necessarily different.

The rest of the paper presents the difficulties of the latter choice, namely the deterministic memory manager, and the solutions we developed in order to obtain a fully operational memory management replay module.

III. Enforcing identical behaviour

It seems pretty straightforward that code handling the recording phase must be as similar as possible to the code that handles the replay phase. Any inconsistency between them can influence the virtual machine, causing different behaviour during record & replay.

However, the record phase and the replay phase are bound to do different things. For instance, record writes data to a trace file, while replay reads from it. This leads to unavoidable differences in code. Luckily, as stated before, in order to produce a faithful replay, all one needs to do is enforcing the non-deterministic items to behave deterministically. In the case of the scheduler for instance, this means enforcing the thread switches at the same logical execution points, independent of the different instrumentation. In case of the garbage collector, this means allocating the same amount of memory at the same logical execution points, also independently of different instrumentation code. The next sections show how to enforce these rules in some of the most interesting situations.

A. Allocation of objects

As the garbage collector is the central issue in this paper, the most obvious system to be affected by the exposed problem must be the allocation system. Indeed, if one wishes that the garbage collector will be invoked at the same execution points in 2 different executions, one must at least allocate the same objects in those executions & use the same amount of stack space.

Obvious, one might think, and indeed, as for the application, this is precisely the task of the record/replay framework. But the instrumentation code itself must also obey this rule. Here rises a problem, as the instrumentation code for the record phase is necessarily different to the instrumentation code for the replay phase.

The problem of the stack space was already solved in [CAN+01]. It is very likely that the 2 phases are forced to use a different amount of local variables and/or stack slots. [CAN+01] presented to preallocate the stack with a certain estimated size that certainly covers all needs during both the record and replay phase. This way, the stack will not be reallocated while executing instrumentation code.

The allocation of objects is another problem however. Using a similar technique as for the local variables would be to enforce a garbage collection every time one enters record/replay dependent code. One will certainly notice that this is a very expensive solution, that won't even work, since objects could still be placed at different addresses on the heap.

Executing dummy allocations of the objects that are only used in the other mode may look as a possible solution at first sight, but there is more. Allocations must also be done in the exact same order, especially in relation to the possible thread switch points. Suppose you're 20 kiB away from a new garbage collection. The order of allocating 2 objects of 10 and 30 kiB each can make a big difference for the execution behaviour. A deep study of the instrumentation code is necessary to result in all allocations (dummy or not) done in the same order during record & replay. However, calls to library code, like writing data to the trace file, make this problem even harder, as one cannot insert dummy allocations in library code. The only way out here is to restrict the use of library code to non-allocating methods. As one might notice, this becomes pretty implementation dependent, as everybody could write a new library class with a different allocation behaviour. In our implementation however we were not restricted by this demand.

B. Lazy compilation

Unfortunately, the allocator is not the only subsystem that gets affected. As will follow, the compiler must also be adjusted to behave similarly during record and replay.

Usually in Java, methods are not compiled until their first execution[1]. Executing different code during record & replay leads as a consequence to compiling different methods. For instance reading some trace information from a file uses different methods as writing that same data. As one may expect, this also influences the garbage collector. Different methods will consume a different amount of memory, leading to different invocation points for the garbage collector, or even non-deterministic out-of-memory errors.

Furthermore, related to the former paragraph (section III-A), there rises another problem, namely that compiling different methods also leads to following another path through the compilercode. This could eventually end up in allocating different objects or consuming a different amount of stack space.

Former solutions to this problem were based on eager compilation [CAN+01]. This technique suggests to precompile every method that could be called from the currently executed one. Since no contemporary JVM supports this type of JIT-compilation (if this is still JIT af-

[1] In the presence of an interpreter, even less methods will be compiled

	unmodifi ed execution (s)	# GCs	recording execution (s)	recording overhead (%)	# GCs	replaying execution (s)	replaying overhead (%)	# GCs
Moldyn A	15.55	2	21.19	36.24	4	21.06	35.41	4
MTRT	26.44	6	37.67	42.46	8	37.21	40.72	8
Monte Carlo A	39.47	5	43.91	11.24	6	43.58	10.42	6
Moldyn B	170.48	2	193.99	13.79	4	193.04	13.23	4
Monte Carlo B	191.26	6	210.58	10.10	8	210.86	10.25	8
JBB	1311.02	110	1345.14	2.60	107	1346.23	2.69	107

TABLE I
TIMING MEASUREMENTS

ter all), and this technique is not efficient at all either, we chose for another solution. We precompile every single method that ever could be called by the instrumentation code, both record and replay. This way, the memory is still filled exactly the same way in both modes, while the inefficiency of unnecesary compiled methods remains restrained to those needed by the instrumentation code, wich is a very small set.

C. Execution frequencies

As a third example, we wish to enlighten one of the problems arising due to the intrusive optimization techniques of a modern JIT-compiler.

Optimizing a particular part of the code in terms of speed often results in using extra memory. One particular and often used technique is inlining a method call. An advanced compiler could choose to make this trade-off between space & time only for hot paths, resulting in gaining lots of time while loosing a small amount of space.

To implement such a strategy, the compiler must collect some information about the execution frequencies of the different paths. This could be done at runtime, but to compile a particular method for the first time, guessing these values is the only solution.

Bearing all this information in one's mind, an inconsistency between record and replay could arise as follows: Suppose one of the gambling techniques is dividing the frequency at every if-test by 2. Also suppose the record mode needs more if-tests than the replay phase. This could result in the code following the recording instrumentation as being cold, while the code following the replaying part to be labeled as hot.

While the hot path through the replay instrumentation continues, it meets a method call to method X, which can nicely be inlined. The same method was seen in the previous recording execution, after following a cold path through the record instrumentation. But in the latter case, the compiler didn't find it necessary to inline, and leaves the method call as is. This finally could result in compilation of method X at different execution points during record or replay, or even worse, in an extra method compilation during the record phase, leading to the same troubles as in the previous section.

The solution we present herefore is to give the control flow graph of the recording code and the replaying code an equal design. This off course follows the general rule that the recording instrumentation and the replaying instrumentation must be as similar as possible.

IV. EVALUATION

In order to prove that this replay mechanism actually works, we have tested it on several multithreaded benchmark applications. The different execution times & amount of garbage collections of these applications can be found in Table I.

MTRT is actually _227_mtrt, the multithreaded Ray Tracer from the JVM98 benchmark suite. The mentioned execution time in Table I is however not the time reported by the JVM98 application, but the total execution time of the JVM98 framework (running in batchmode) together with the specified benchmark. This is because, as DejaVu replays the wall clock, the replayed benchmark test reports that is has run exactly as long as the recorded one. It doesn't know any better.

Monte Carlo and Moldyn are two multithreaded applications from the Java Grande suite, which we ran both with 10 threads. Java Grande specifies 2 data sets, a smaller one (the 'A' version) and a larger one (the 'B' version). Here too, we didn't use the reported performance measurements for comparison, but the actual execution time. Remark however that the performance slowdown of the record phase resembles pretty much the overhead in execution time.

JBB is the JBB2000 benchmark, ran with standard input

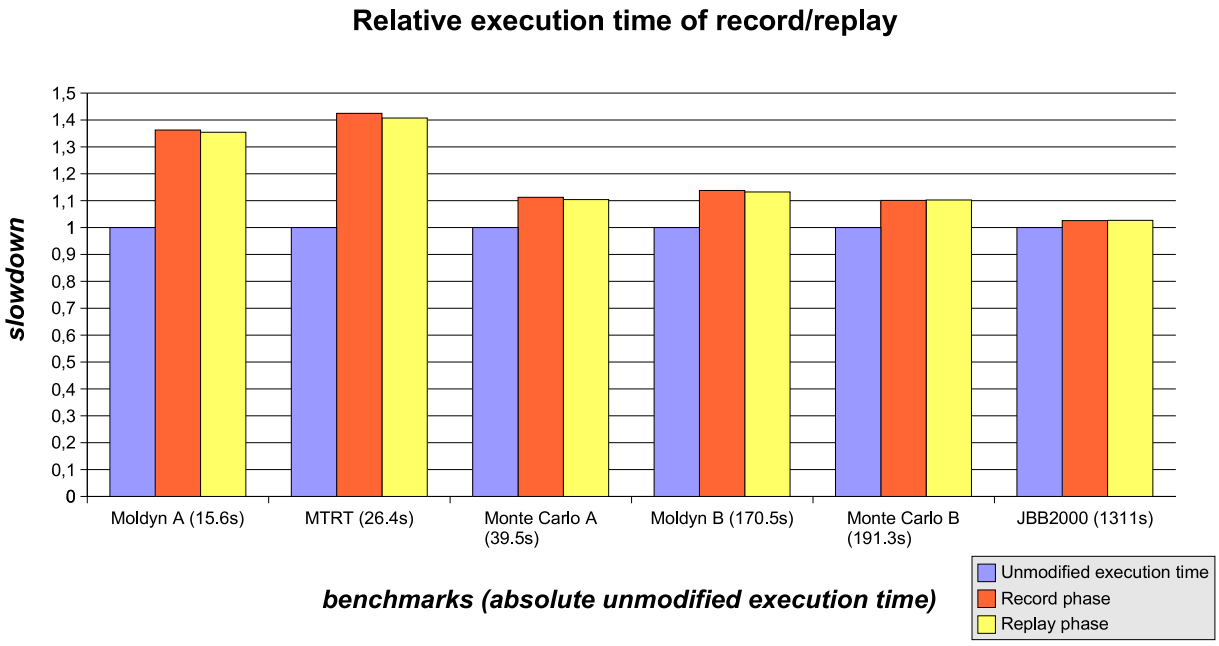

Fig. 1. Results

parameters, namely 8 warehouses, 30 seconds rampup & 2 minutes of transaction time.

As one can see in figure 1, the overhead significantly drops with longer execution time. DejaVu has a high impact on the compilation time. While most of the applications are quite small programs, they spend relatively much time compiling, wich explains the high overhead. A small overhead of 2% remains during large applications as JBB. Remark however that, for JBB, the difference in reported throughput between the unmodified execution and the record phase varies between 2 & 10%. The replay phase reports naturally the same throughput as the record phase.

Table I also shows the number of garbage collections in each run. For every execution, the necessary heap space was measured on the short side, in order to enforce garbage collection more often. This explains why for some executions the amount of GCs in the record/replay phases is twice as much as for the unmodified execution phase. The most important issue here is of course that record and replay have the same number of collections. No need telling that the execution points of each collection during resp. record and replay are exactly the same.

In case one wonders why the unmodified execution of JBB has more GCs than the recording phase, this is due to the decreased throughput in the latter phase. Less throughput leads to less allocations, implying less garbage collections. This also implies that the record/replay framework doesn't use too much extra memory, despite what one could conclude from the smaller numbers.

Although one might think that performance measurements are important, the most important thing is that the recorded execution and the replaying execution actually produce the same results. The above timing measurements are definitely susceptible for optimization, but one thing is not changeable, namely that all applications generate exactly the same output during record and replay. For the Java Grande and the JVM98 benchmarks for instance, this means that they produce exactly the same performance measurements. With JBB, this means the same amount of transactions, thread spread, heap usage, sequence of started warehouses and so on.

V. Conclusions & future work

With this paper, we have revealed some of the difficulties of a record/replay tool in the presence of a garbage collector. For each one, we have presented a solution. We have also shown that our proposals actually work for modern virtual machines, and with an acceptable overhead.

In the future, we should design a debugging platform on top of our record/replay framework. This way one could easily follow variables, place breakpoints and so on. The most difficult obstacle will probably be the influence of the debugger on the virtual machine, as this could also disturb the replayed execution. A good start is already given by [ACN+01].

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